Effect of Foundation Displacement on Strength Degradation and Member Damage of Electric Transmission Tower

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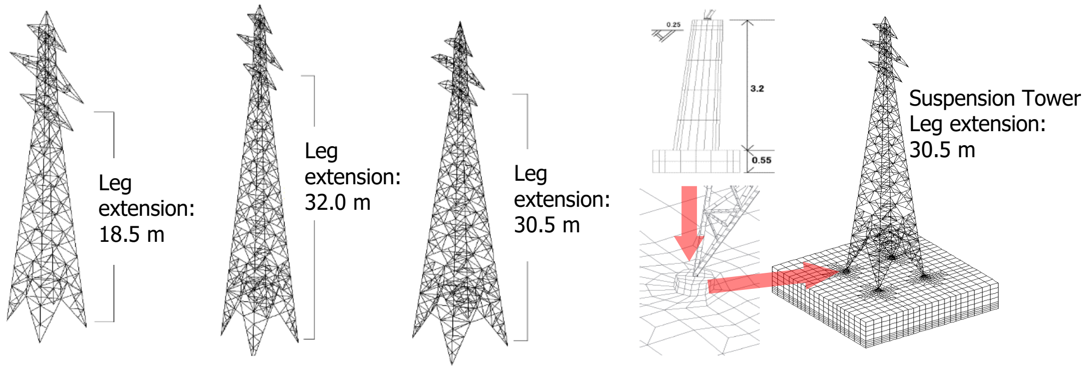
1. Introduction

In recent years, transmission towers have been subjected to damages due to uneven foundation displacement caused by ground deformation, such as landslide, subsidence, etc. This research examines the effect of uneven foundation displacement on member damages, such as buckling and plastic yielding, as well as strength degradation of a transmission tower. Realistic external loads used in the standard design code, including tower's own weights, tension forces of transmission cables, and wind loads that vary with seasons are introduced as an equivalent nodal force vector in the finite element analysis. The ultimate strength of the tower under imposed uneven foundation displacement is estimated by a load factor of the design load. The uneven foundation displacements with various magnitudes and directions are introduced in the analysis as an enforced nodal displacement at the support of tower and these effect is discussed. In order to examine the effect of support stiffness [1, 2], we also consider "uncoupled model of transmission tower" and "soil-foundation-tower fully coupled model" shown in **Figure 1**.



(a): Uncoupled Model **(b)**: Soil-foundation-tower Coupled Model

Figure 1: Finite Element Analysis Model

2. Method & Results

Two different types of transmission tower are considered in this study. Suspension tower is generally used in a light-angled transmission line, in which the horizontal stationary load acting on the cross arm is relatively small. In this type of tower, the cable is supported vertically using suspension insulators. Tension tower is used in a heavy-angled transmission line, so that large horizontal stationary load acts directly on the cross arm. In this type of tower, the cable is attached to the cross arm through strain insulators, which resist net tension of the cable. In the analysis of uncoupled tower model (**Figure 1(a)**), suspension tower (body/leg extensions: 18.5m & 32.0m) and tension tower (body/leg extension: 30.5m) are considered to examine the effect of body/leg extension. In the coupled model shown in **Figure 1(b)**, a whole structural system consisting of soil ground, concrete pile foundation, and steel transmission tower is modeled, in which the suspension tower with the body/leg extension of 32.0 m is considered. The towers consist of steel angle members with L-shaped cross section. To simplify the analysis using beam elements available in our in-house FE analysis code, the angle members are converted to beams with box-shaped cross section having equivalent cross-sectional properties (**Figure 2**). The von Mises and Drucker-Prager plasticity models are adopted to model the steel material and the ground soil, respectively. The reversed T-shaped concrete pile foundation is modeled as elasticity ignoring its failure. An external load setting according to the Japanese design standard for towers is adopted in the analysis, in which seasonal differences of the cable tension, wind pressure, accretion thickness of snow and ice, are considered.

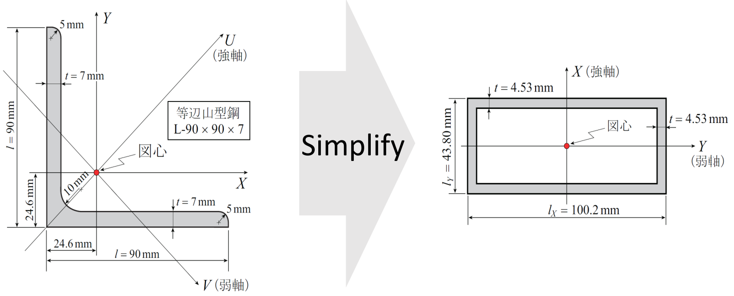
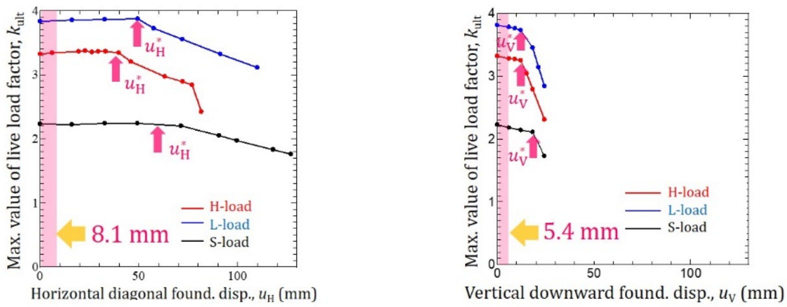


Figure 2: Simplification of L-shaped Cross Section of Angle Members to Equivalent Box-shaped Cross Section

Three dimensional nonlinear finite element method based on the finite strain elasto-plasticity theory is utilized in the analysis. The design load is decomposed into dead load $\mathbf{F}_D$ and live load $\mathbf{F}_L$, namely,

$$\mathbf{F} = \mathbf{F}_D + k\mathbf{F}_L \ , \tag{1.1}$$

where k denotes the live load factor, which is used as a load-controlling parameter in the analysis. The analysis procedure for a tower subjected to uneven foundation displacement is described in the following. First, the dead load is applied to the tower. Then, a specified value of foundation displacement in horizontal diagonal direction or vertical downward direction ($u_H$or u_V) is enforced to a support of the tower at a leeward side. The live load is applied by increasing the live load factor k. The ultimate strength of the tower k_{ult}, with/without imposed foundation displacement is obtained. **Figure 3(a)** and **(b)** plot k_{ult} as a function of imposed horizontal and vertical foundation displacement, respectively, comparing the effect of three different seasonal loads: Typhoon season (H-load), Winter season (L-load), and Wet snow accretion case (S-load). By this plot, strength degradation due to a specific value of the foundation displacement can be evaluated directly. One phenomenon can observe that the tower retains its original strength within a certain limit of foundation displacement, whereas the tower exhibits abrupt decrease and significant loss of its strength when the foundation displacement exceeds the limit value. It should be also noted, however, that the limit value of the foundation displacement depends on the direction of imposed foundation displacement as well as the assumed seasonal loads. The zone colored in red in the figure means the admissible range of foundation displacement specified in the Japanese technical guideline. The values of admissible tolerance are specified as 1/800 and 1/1200 of the leg span for horizontal and vertical foundation displacement, respectively. In the present case, 8.1 mm and 5.4 mm for a leg span of 6.48 m. We can confirm that a certain safety margin is secured in the present case, while the vertical foundation displacement is more severe and influential to the strength degradation than horizontal one.



(a) **(b)**

Figure 3: Analysis Results of Uncoupled Tower Model

In the following, the analysis of soil-foundation-tower coupled system (**Figure 1(b)**) is presented. The ground soil is modeled by a constitutive model based on Drucker-Prager plasticity, and a series of analysis for various soil properties (Ground A to E) is performed to examine the effect of support condition. Ground A (c=10 kPa, φ=20°) assumes a relatively soft ground, while Ground E (c=30 kPa, φ=40°) assumes a hard ground. As a comparison reference, the analysis of a transmission tower with fixed supports is also conducted using uncoupled tower model. **Figure 4** shows the analysis results of load versus tower deflection relationship obtained by a series of coupled analysis for Ground A to E without imposing foundation displacement. The analysis result reveals that the ultimate strength tends to decrease when the foundation displacement exceeded a certain value, while the decrease of ultimate strength is quite different depending on the ground condition. **Figure 5** plots the strength degradation due to imposed foundation displacement u_H, which reveals that in the coupled analysis, the tower strength in its soundness retains almost constant without significant degradation even after very large foundation displacement, while a slight decrease of strength is observed in Ground C (moderately hard ground). This is in contrast to uncoupled tower analysis. The other one should note, however, that in the coupled analysis for Ground A plotted in **Figure 4**, apparent deflection is caused by soft ground deformation, although it is not tower deflection but actually rigid tilting due to ground deformation.

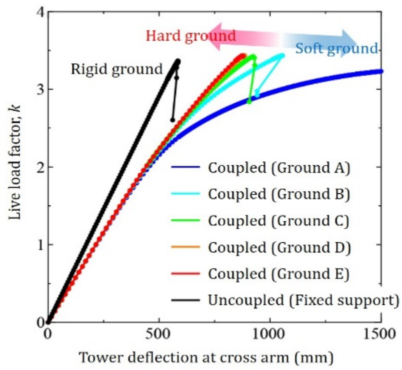


Figure 4: Analysis Results of Load-deflection Curve in Coupled/uncoupled Analysis

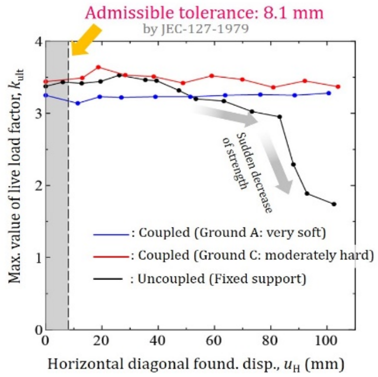


Figure 5: Analysis Results of Strength Degradation

3. Conclusion

In 'uncoupled FE analysis model of a tower' part:

- Safety margin of the design load, compared with the ultimate strength of the tower in its initial soundness (without foundation displacement), is significantly different depending on the seasonal loads.
- The ultimate strength tends to decrease abruptly when the foundation displacement exceeds a certain limit, while the trend of decreasing strength depends on the tower type, seasonal load, and the direction of foundation displacement.
- The vertical foundation displacement is more influential to on the strength degradation than the horizontal one.

In 'coupled soil-foundation-tower FE analysis model' part:

- In the coupled analysis of whole tower system, no significant loss of ultimate strength is observed even after enforcing large foundation displacement.
- The bearing stiffness of pile foundation has a significant influence to the failure mode of the tower subjected to foundation displacement.
- The above result implies that a loosely supported leg would alleviate damage to the tower to a certain extent, particularly damages to members around legs due to foundation displacement.

Acknowledgements

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